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Photometric charge determination of relativistic heavy primaries in cosmic radiation

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With 7 figures in the text

SUMMARY

A photometric method of determining the charge of relativistic heavy primary particles in photographic emulsions is described. Corrections for different emulsion effects are applied. The accuracy of the charge determination in the interval $3 \leqslant Z \leqslant 14$ is very good. The standard error corresponds to about one fifth of the distance between consecutive charges. The method may also be used for higher charges.

The charge spectrum is studied in the interval $3 \leqslant Z \leqslant 14$ in emulsions flown over Texas at 41° geomagnetic latitude. The mean flight altitude was about 29 km corresponding to 14 g/cm^2 overlying atmosphere. The charge calibration is made by δ-ray counting and by studies of fragmentation of heavy nuclei in the emulsion. An extrapolation of the number of boron particles to the top of the atmosphere shows that there exists a finite flux of these particles in the primary beam. The abundance ratio N_{Boron}/N_M falls in the interval 0.13 to 0.25, depending on the fragmentation probabilities used for the extrapolation. The results further show that the relative frequency of nitrogen nuclei is small compared with the frequency of carbon and oxygen nuclei. These nuclei occur in comparable amounts.

Introduction

As a result of measurements carried out at high altitudes with nuclear emulsions, counters, and cloud chambers [1–38] it has been established that the primary cosmic rays are composed of protons, α-particles and a small amount of heavier nuclei. It has proved to be of primary importance to know the accurate charge distribution of the primary radiation in order to understand the origin and the accelerating mechanism. Up to the present, however, no identification method has given a complete resolution between consecutive charges in the whole charge interval $3 \leqslant Z \leqslant 26$.

This paper describes measurements on heavy tracks in photographic emulsions with a photoelectric measuring technique. The method gives a satisfactory resolution between consecutive charges in the charge interval $3 \leqslant Z \leqslant 14$ and may also be used for higher charges.

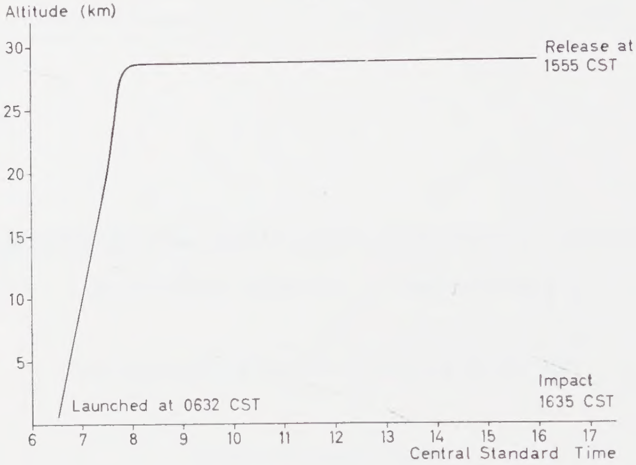

Fig. 1. Time–altitude curve for the balloon flight.

Emulsion stack and exposure details

The stack consisted of 40 stripped Ilford G 5 emulsions 7.5×10 cm, 600 μ thick, enclosed in an airtight aluminium container with a wall thickness of 1 mm. It was flown by the U.S. Navy at San Angelo, Texas, U.S.A. on January 13, 1955. The time–altitude curve for the flight is shown in Fig. 1. The mean altitude during the flight was 29 km, which is equivalent to an overlying atmosphere of 14 g/cm^2. The thickness of the container and of the packing material corresponds to 1 g/cm^2.

Processing and preparation for measurement

After exposure the plates were mounted on glass and processed at Lund with the usual temperature development method. The blob density for relativistic singly-charged particles was found to be 19 blobs/100 μ.

The plates were mounted on aluminium frames and aligned; partly X-ray marks and partly the tracks of relativistic heavy nuclei were used. It was then very easy to trace a track from one plate to the next.

Scanning and scanning criteria

The plates were scanned for tracks satisfying the following criteria:

(*a*) the track should have a grain density greater than 6 times the minimum value,
(*b*) the projected track length should exceed 3 mm/plate, and
(*c*) the track should have a zenith angle less than 60°.

The scanning was performed by one very experienced observer and a rescanning of two plates showed no discrepancy at all. No detailed investigation of the scanning efficiency was undertaken as the main aim of this experiment was to develop a new method of charge determination for relativistic heavy nuclei. However, there seems to be no systematic loss of tracks of particles with a charge of $Z > 4$. Some of the Li-tracks and a few of the Be-tracks may possibly have been lost in the great background of slow protons and α-particles.

Photometric instrument and the measurements

The photoelectric apparatus has been described by von Friesen and Kristiansson [39], and by von Friesen and Stigmark [40]. It consists in principle of two parts, a microscope part for the measurements proper and an electronic part for their registration. The microscope part consists of a Leitz microscope with a Ks 53× objective. The place of the ordinary eye-piece is taken by an eye-piece of special construction. There is a slit in its image plane, and above this slit a photomultiplier which registers the amount of light passing through. The dimensions of the slit referred to the object plane were in this investigation $54\,\mu \times 4.3\,\mu$. The slit admits a very small part of the field of view around the image of the $54\,\mu$ long section of the track which is to be measured. The amount of light passing through the slit is proportional to the area of the slit minus the projected area of the track. If the track and the slit are moved relative to one another to a position where the track falls outside the slit, the amount of light which now passes through it is proportional to the total slit area. The difference between this "background" reading and the reading with the track in the slit is proportional to the projected area of the track. The main features of this part of the apparatus have been described in the paper by von Friesen and Kristiansson [39]. Some improvements for increasing the speed with which the measurements can be made have been described in two later papers [40, 41].

The photomultiplier is connected to a Leeds and Northrup Speedomax recorder via a linear amplifier. This amplifier and the high tension supply for the photomultiplier have been described by von Friesen and Stigmark [40].

In measurements with this type of apparatus on singly-charged particles the background was measured on both sides of the track in the horizontal plane and a mean value of the two readings was calculated. For singly-charged particles the number of δ-rays is small and the background measurements could be made very close to the track. However, for relativistic heavy particles the number of δ-rays is large and the background measurements must be made relatively far from the track owing to the long δ-rays. It has been found that the lateral displacement must be about $10\,\mu$ to make the error as small as possible. For a smaller displacement the δ-rays give trouble, and at larger displacements the error in MTW will increase rapidly owing to irregularities in the emulsion. Purely instrumental reasons make it difficult to make the lateral displacement with sufficient precision if it has to be done rapidly. We have found that owing to the construction of the microscope the background measurements can be made above and below the track instead without increasing the relative error. Therefore, one background reading was taken $30\,\mu$ above and another $30\,\mu$ below the track, and a mean value of the two readings was calculated.

The measurement of a track was made in the following way. As mentioned above the plates were fixed in aluminium frames. These frames were then placed in another frame which could be rotated on the microscope stage. The frame was turned until the track became parallel to the x-axis. Every track was measured in the depth interval $100\,\mu$ from the glass to $100\,\mu$ from the surface. The emulsion being $600\,\mu$ thick,

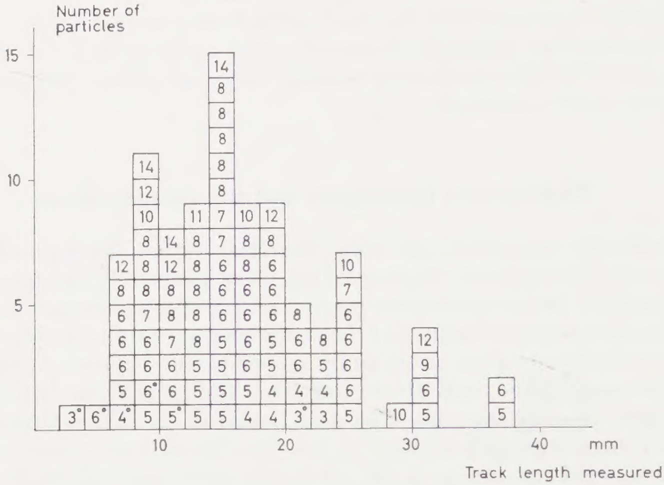

Fig. 2. The number of particles versus the track length measured. The numbers in the squares indicate the charge of the particle. The secondaries are marked with an open circle.

this means that 2/3 of the track length has been measured in each plate. The reason for this procedure is to avoid such parts of the emulsions in which disturbances from the processing of the plates may appear. The displacement along the track between two consecutive measurements was 50 μ. The same track was measured in different plates until the track length measured amounted to about 15 mm. The distribution of the track lengths measured can be seen in Fig. 2. The numbers in the squares indicate the charge of the particle.

A track in a photographic emulsion from a relativistic heavy nucleus can in principle be divided into two parts, the central core and a number of δ-rays of different lengths. When the track is placed in the slit the long δ-rays fall outside the slit. This cutting off of the long δ-rays means that the MTW values will be smaller than the values obtained with a slit covering the core and all δ-rays. The part of the track which gets cut off depends on the charge, it being always the same for the same kind of particle. It can, therefore, be expected that the MTW values for different particles with equal charge will be the same.

Depth correction

As has been described by Kristiansson [39, 42] and Waldeskog [43], the MTW values must be corrected for the depth in the emulsions. The ionization along the track of a heavy relativistic particle being constant, the correction factors can be obtained directly from the measured MTW values. It can be expected that the correction factors will vary with the ionization. In order to investigate this, the depth–MTW relations have been calculated for each of the charges $Z = 4$, 6, 8, 10, and 12 (Fig. 3). The correction factors obtained from these curves are seen in Table 1. The mean value in the last column has been used for the corrections in the whole charge interval $3 \leqslant Z \leqslant 26$.

The error in the MTW values introduced by using these mean correction factors can

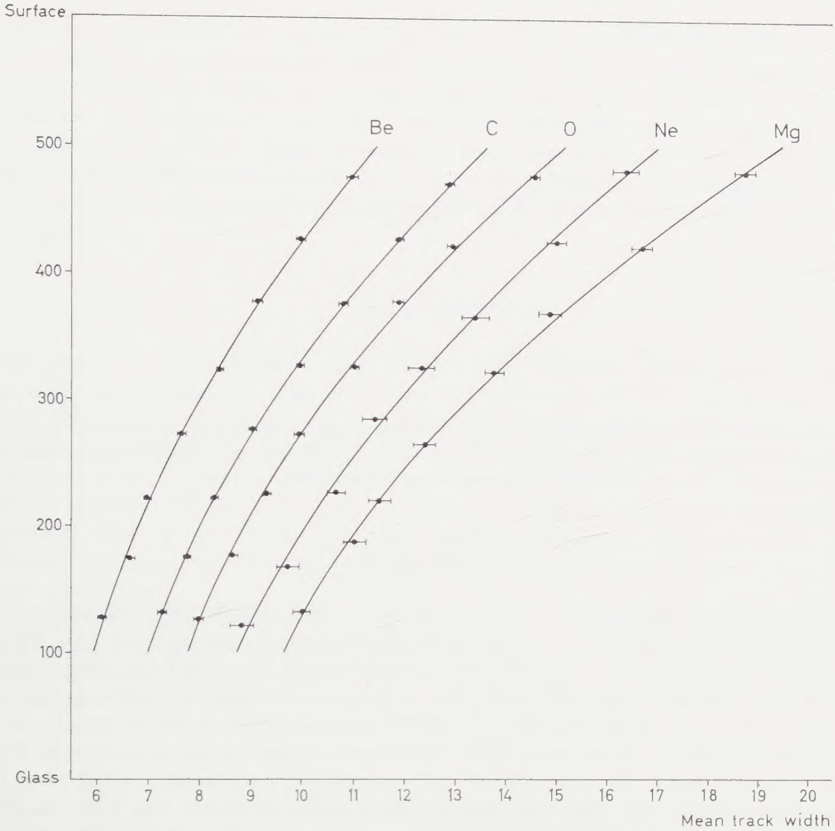

Fig. 3. The relation between the uncorrected mean track width (MTW) values and the depth in the emulsion for five different charges ($Z = 4, 6, 8, 10$, and 12). The depth is expressed in microns and is referred to undeveloped emulsion.

be neglected in the charge interval $3 \leqslant Z \leqslant 12$. There will be a non-negligible error for the charges $Z \gtrsim 16$. But as all tracks are measured in the same depth interval the same error will be introduced; this means that tracks from particles with the same charge must give the same MTW value. Only the distance between consecutive charges expressed in MTW units will be influenced. The systematic error in the MTW values for charges about $Z = 26$ can be estimated to $< 1\,\%$.

Table 1.

d (μ)	Z					Mean value
	4	6	8	10	12	
100	0.699	0.693	0.689	0.699	0.682	0.692
200	0.838	0.834	0.833	0.837	0.827	0.834
300	1.000	1.000	1.000	1.000	1.000	1.000
400	1.176	1.181	1.177	1.182	1.191	1.181
500	1.347	1.351	1.336	1.364	1.376	1.355

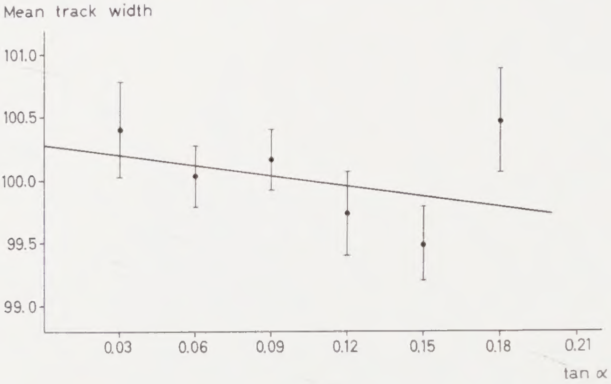

Fig. 4. The mean track width (MTW) values in arbitrary units versus tan α, where α is the dip angle in unprocessed emulsion. All the particles with charge $Z = 5$, 6, 7, and 8 have been used after the appropriate normalization.

Dip correction

The influence of the dip angle, α, on the results of mean track width measurements has been studied for singly-charged particles in previous investigations [41, 42]. In this investigation the minimum projected track length accepted for measuring a track was 3 mm/pellicle. That corresponds in unprocessed emulsion to $\alpha = \arctan 0.2$. To investigate the error from the dip, the MTW values obtained for all tracks in the charge interval $5 \leqslant Z \leqslant 8$ have been used. The mean values of the 4 groups in Fig. 6 ($Z = 5$, 6, 7, and 8) have been calculated and normalized to the same level of MTW, which has been called 100. The appropriate normalization factor has been used for each track. The normalized MTW values were plotted against tan α (Fig. 4); and a straight line fitting these values was drawn with the least square method. From the figure it can be seen that the difference in MTW values between tan $\alpha = 0$ and tan $\alpha = 0.20$ is about 0.5 %. As the smallest distance between consecutive charges in the interval $3 \leqslant Z \leqslant 14$ is > 5 %, the error introduced by not correcting for the dip is less than 0.1 unit of charge.

Batch normalization

Out of the stack of 40 pellicles only 24 were used for the measurements. These 24 pellicles were processed in batches of 6. In the following the batches have been numbered 1, 2, 3, and 4. The different processings were made as similar as possible, but, in spite of this, differences can be observed in the degree of development between the different batches and also between the different plates within one batch. A normalization factor has been determined for each batch containing 6 plates. This was done in the following way. For each batch the particle frequency was plotted against the measured MTW value. A number of groups was obtained and a mean MTW value was calculated for each group. Many tracks were traced through and measured in two or more batches. Consequently, there was no difficulty in identifying corresponding groups in consecutive batches. The quotients between the MTW mean values in batch 1 and corresponding values in batches 2, 3, and 4 were calculated. The weighted mean values of these quotients determine the normalization factors for batches 2, 3, and 4 in relation to batch 1. As our material was too small to determine a normalization factor for each individual plate we have restricted our investigation as far as possible to tracks which pass through at least one whole batch. In this way those errors were avoided which would have been introduced if only some of the 6 plates in a batch had been measured. Only a few of all the measured tracks do not fulfil this condition.

Charge calibration

The photometric method is only relative and therefore no absolute values can be obtained for the charges directly from the measured MTW values. One can only expect that tracks of relativistic particles with the same charge will group themselves around a mean value on the MTW axis. In Fig. 6 part of the results of our measurements is shown. From the figure it can be seen that we have obtained very well resolved groups. To identify the particles in a group, some kind of calibration is necessary. One of us, O. M. [44], has made a thorough calibration by the δ-ray counting method, and further we have studied some heavy particle fragmentations in the emulsions.

The most common method to determine the charge of heavy relativistic primaries in photographic emulsions is the δ-ray counting method. The reason is the simple relation between the δ-ray density, n_δ, and the charge of the relativistic particle

$$n_\delta = a + b\,Z^2$$

where a and b are constants. However, this method has not given a full separation between consecutive charges even in the charge interval $3 \leqslant Z \leqslant 10$. For charges $Z > 10$ the method seems to be unreliable.

On interpreting the results of our photometric measurements, two assumptions were made. We assumed that different groups were not composed of particles with the same charge and that the difference in charge between adjacent groups was one charge unit. In order to confirm this δ-ray counting was performed on a number of tracks [44]. The δ-ray measurements were restricted to tracks of particles in the charge interval $2 \leqslant Z \leqslant 10$, and only tracks already measured with the photometric method were used. The counter was given tracks chosen from different groups in the MTW spectrum that were unknown to him. On each track at least 100 δ-rays were counted according to a special convention. After finishing the work the counter obtained the values of the charges assumed from the photometric measurements, and the results of the two methods were compared. This comparison confirms our first assumption but could not directly confirm the second. There was a slight possibility that we had lost a group between the groups called Li and Be. To get a confirmation of our second assumption we had to use the information obtained from interactions between the heavy cosmic ray particles and the emulsion nuclei. In the charge interval $3 \leqslant Z \leqslant 10$ we found four interactions in which only relativistic fragments with charge $Z \leqslant 3$ were produced and in which charge balance was obtained between these relativistic fragments and the splitting nucleus if the charge calibration from the photometric measurements was used. These fragmentations are shown in Table 2.

Table 2.

Measured charge of the primary particle	Assumed interaction
6	$C \rightarrow 2\,\alpha + 2\,p$
6	$C \rightarrow 2\,\alpha + 2\,p$
6	$C \rightarrow 1\,Li + 3\,p$
10	$Ne \rightarrow 3\,\alpha + 4\,p$

The values in the table confirm our second assumption and reject the possibility of a group between those called Li and Be, since the true charge cannot be greater than the assumed charge.

These discussions make it clear that our assumptions about the charge for the different groups are correct up to $Z = 10$.

In Fig. 5 the calibration curve can be seen. The MTW mean values of the different groups in Fig. 6 have been plotted against the charge. To judge from the discussions above, the curve must be correct up to $Z = 10$. The curve has been drawn continuous to $Z = 14$ and then dotted to $Z = 26$. The extrapolation to $Z = 14$ seems to be justifiable because the MTW values obtained from the curve for $Z = 12$ and $Z = 14$ agree with the two small particle groups in the MTW region 13 and 15 in Fig. 6. It is not unreasonable to assume that Mg ($Z = 12$) and Si ($Z = 14$) are more abundant in

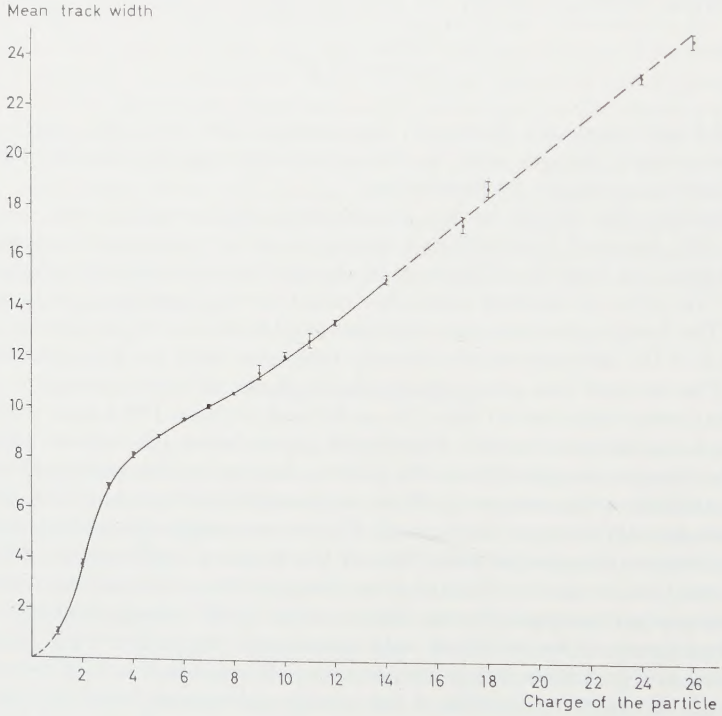

Fig. 5. The relation between the mean track width (MTW) and the charge of the particle.

radiation than Na ($Z = 11$), Al ($Z = 13$) and P ($Z = 15$), because Mg and Si are much more abundant in the universe than adjacent odd charges [45]. The dotted part of the curve is a very rough extrapolation. A fragmentation of a particle identified as Cr ($Z = 24$) into one A ($Z = 18$), one Li ($Z = 3$), one α-particle ($Z = 2$), and one singly-charged particle ($Z = 1$) gives us an idea of the form of that part of the calibration curve. If the dotted extrapolation is accepted, the greatest measured MTW value corresponds to charge $Z = 26$ (Fe). In the following discussion this very heavy part of the spectrum has not been considered.

The calibration curve in Fig. 5 can be explained qualitatively in the following way. The measured mean track width value can in principle be divided into two parts, one being a contribution from the grains in the central core and the other being from the grains in the δ-rays. A track of a singly-charged fast particle consists of a number of free grains in the core and of practically no δ-rays. In a track of an α-particle most of the grains in the core are still free and the δ-rays are few. For tracks thinner than α-particle tracks MTW is approximately proportional to the ionization. When the ionization increases, a saturation effect sets in and the proportionality will be lost. The number of grains in the core will gradually reach a constant value, the completely filled core. This limit is reached at about $Z = 8$.

The contribution to the MTW from the δ-rays was unimportant for charges 1 and 2, but, since the number of δ-rays is proportional to Z^2, it will be of increased importance for higher charges; and the slope of the MTW $- Z$ relation will increase again. As can be seen from Fig. 5 the calibration curve has an inflexion point in the region around $Z = 7$, and thus the difference in MTW values between consecutive charges passes through a minimum. In the charge interval $3 \leqslant Z \leqslant 10$ it may therefore be expected that the charge resolution will not be so good in the region $6 \leqslant Z \leqslant 8$ as in other parts of the interval.

Results

The charge spectrum obtained from the photometric measurements in the charge interval $3 \leqslant Z \leqslant 14$ is represented in Fig. 6. The position of the arrows was determined from the calibration curve (Fig. 5). The tracks marked with a white dot are

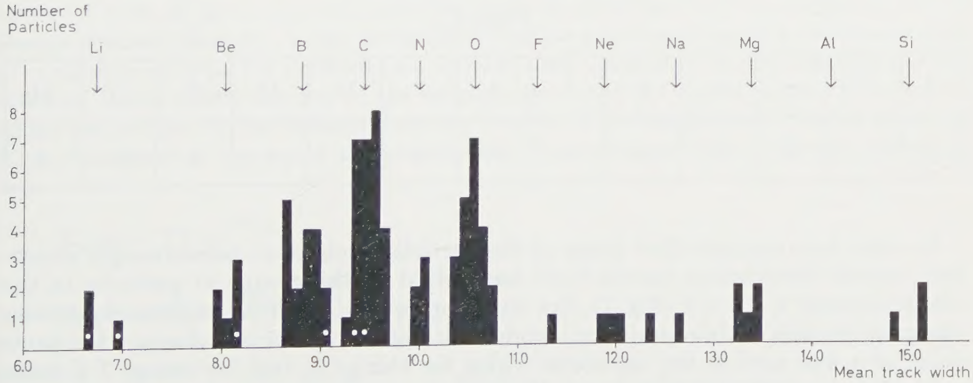

Fig. 6. The number of particles versus the mean track width (MTW). The secondaries are marked with a white dot. The position of the arrows has been determined from the calibration curve (Fig. 5).

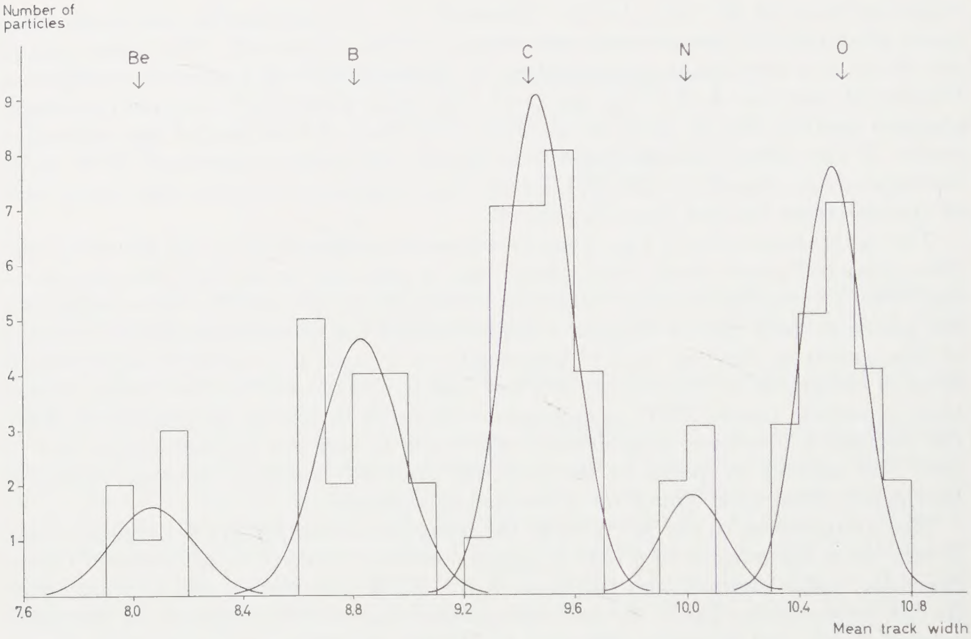

Fig. 7. The relation between the number of particles and the mean track width (MTW) in the charge interval $4 \leqslant Z \leqslant 8$ with normal distributions inserted. For the charges $Z = 4$ and 7 the standard deviation has been computed from data of the other charges (see text). The position of the arrows is determined from the calibration curve (Fig. 5).

fragments of heavier nuclei which have collided with nuclei in the emulsion. All other tracks are primaries, if primaries are defined as particles entering the stack. The figure shows a well-resolved charge spectrum in the whole charge interval $3 \leqslant Z \leqslant 14$. The frequency, N, of primaries of different charges is seen in Table 3.

Table 3.

Z	3	4	5	6	7	8	9	10	11	12	13	14
N	1	5	16	25	5	21	1	4	1	5	0	3

In order to investigate how many of the particles could have been wrongly identified, normal distribution curves have been fitted to the groups of particles in the charge interval $4 \leqslant Z \leqslant 8$ (Fig. 7). For the charges 5, 6, and 8 the number of particles was great enough to determine the standard deviations σ. For the charge 4 the same value of σ was used as the calculated value for charge 5, and for charge 7 a mean value of the σ:s for 6 and 8 was used. The standard deviations together with the mean MTW values are shown in Table 4.

Table 4.

Z	σ MTW-units	MTW
4	(0.15)	8.03
5	$0.15 \pm .03$	8.81
6	$0.12 \pm .02$	9.44
7	(0.115)	10.00
8	$0.11 \pm .02$	10.56

From Table 4 it can be calculated that half the distance between consecutive charges corresponds to about 2.5 σ. There are some experimental indications that the value 2.5 σ will not decrease appreciably for charges up to $Z = 14$, and that therefore probably very few of the particles have been wrongly identified.

Discussion

One of the important problems in the study of cosmic radiation today is the existence or non-existence of the light nuclei Li, Be and B in the primary beam. To obtain an answer to this question it is necessary to extrapolate the charge spectrum at the flight altitude to the top of the atmosphere. It is known that in interactions of heavy nuclei, nuclei of lower charge are emitted as fragmentation products and that therefore a straight exponential type of extrapolation is not appropriate. In order to obtain the flux of light and medium nuclei, a set of one-dimensional diffusion equations must be considered. The charge spectrum is divided into three parts defined in the following way: the light group L ($3 \leqslant Z \leqslant 5$), the medium group M ($6 \leqslant Z \leqslant 9$), and the heavy group H ($Z \geqslant 10$). The diffusion equations can be written [14]

$$\frac{d N_I(x)}{d x} = -\frac{N_I(x)}{\lambda_I} + \sum_{I' \geqslant I} \frac{P_{I'I} N_{I'}(x)}{\lambda_{I'}}$$

where $I = H$, M or L, λ_I is the mean free path in g/cm² for the Ith component of the heavy element flux, $P_{I'I}$ is the probability that in an interaction of a nucleus of type I' a nucleus of type I is emitted, $x = h/\cos\theta$ is the amount of matter traversed, h the vertical depth below the top of the atmosphere and θ the zenith angle. These equations are subject to the initial condition $N_I(0) = N_I^\circ$ = the primary flux of nuclei of type I incident at the top of the atmosphere. The solutions of the diffusion equations are:

$$N_H(x) = N_H^\circ \cdot e^{-x/\lambda'_H}$$

$$N_M(x) = N_M^\circ \cdot e^{-x/\lambda'_M} + \frac{N_H^\circ P_{HM}}{\lambda_H} \beta_{HM}$$

$$N_L(x) = N_L^\circ \cdot e^{-x/\lambda'_L} + \frac{N_H^\circ P_{HL}}{\lambda_H} \beta_{HL} + \frac{N_M^\circ P_{ML}}{\lambda_M} \beta_{ML} + \frac{N_H^\circ P_{HM} P_{ML} \alpha_{HM}}{\lambda_H \lambda_M} (\beta_{ML} - \beta_{HL})$$

where

$$\lambda_I' = \lambda_I \frac{1}{1-P_{II}},$$

$$\alpha_{IJ} = \frac{\lambda_I' \lambda_J'}{\lambda_J' - \lambda_I'},$$

$$\beta_{IJ} = \alpha_{IJ}\left(e^{-x/\lambda_J'} - e^{-x/\lambda_I'}\right).$$

In the three equations above the first term on the right-hand side represents the absorption of the incident flux of type I, and the other terms represent contributions to this flux at depth x due to interactions of heavier nuclei.

We had to make two extrapolations, first through the amount of emulsion traversed before detection of the track and secondly through the amount of atmosphere traversed. The mean value for the depth in the emulsion is equal to 12 g/cm^2, and in the atmosphere to 18 g/cm^2. The number of interactions in our material was too small to determine the different constants P_{IJ}. The extrapolations were performed with three sets of constants taken from publications by Noon *et al.* [17], Rajopadhye *et al.* [33], and Cester *et al.* [30]. The values for λ_I were taken from a publication by Cester *et al.* [30]. As mentioned above, the scanning efficiency for the tracks of Li and Be was probably not very good. Only the boron group therefore was taken into consideration at the extrapolation of the L-group. This change entails that for the constants P_{HL}, P_{ML}, and P_{LL} must be substituted P_{HB}, P_{MB}, and P_{BB}, where the index B stands for boron. Investigations performed by Rajopadhye *et al.* [33] and Cester *et al.* [30] in emulsions, and by Hopper *et al.* [46] in water loaded emulsions show that there exists with good approximation the same probability for each of the three nuclei, Li, Be, and B, to emerge as fragments at interactions between heavier nuclei and nuclei of the emulsion or the atmosphere. Therefore we have put $P_{HB} = \frac{1}{3} P_{HL}$, $P_{MB} = \frac{1}{3} P_{ML}$, and $P_{BB} = \frac{1}{3} P_{LL}$. One third is probably an upper limit of this factor. At a depth of 12 g/cm^2 emulsion the charge spectrum consisted of 16 boron nuclei, 53 M-nuclei and 16 H-nuclei. The results of the extrapolation are given in Table 5.

Table 5.

Fragmentation probabilities according to	$\overset{\circ}{N}_H$	$\overset{\circ}{N}_M$	$\overset{\circ}{N}_B$	$\overset{\circ}{N}_H/\overset{\circ}{N}_M$	$\overset{\circ}{N}_B/\overset{\circ}{N}_M$
Noon *et al.*	41.4	106.0	13.4	0.39	0.13
Rajopadhye *et al.*	40.1	95.8	23.8	0.42	0.25
Cester *et al.*	37.7	100.4	19.1	0.38	0.19
Mean value	39.7	100.7	18.8	0.40	0.19

From the table it can be seen that the different constants, P_{IJ}, used for the extrapolation do not very much influence the flux value of the H- and M-nuclei. The greatest difference from the mean value is about 5 %. However, the flux of the boron nuclei is very sensitive to the value of the constants. Here the greatest difference from the mean value is about 30 %. In spite of this, it can be concluded that there exists a finite flux of boron nuclei at the top of the atmosphere.

Table 3 shows that nitrogen nuclei are less abundant than carbon and oxygen nuclei. In the extrapolation these three nuclei together with fluorine were considered as a unit, the M-group. On account of insufficient knowledge of fragmentation probabilities it is impossible to calculate the relative frequency of the four nuclei at the top of the atmosphere. However, it can be estimated that their relative frequency will not be very different from the measured one. A comparison between the measured relative frequencies shows that carbon and oxygen nuclei occur in comparable amounts and more often than nitrogen nuclei. This result is in agreement with that of Bradt and Peters [5] but in disagreement with the results obtained, for example, by Kaplon *et al.* [14] and Dainton *et al.* [12].

As the universal abundance of the L-elements can be neglected in comparison with the M-elements [45], we have tried to perform an extrapolation to the source of the primary beam on the assumption that the boron abundance at the source has been zero. The values for the constants P_{IJ} have been taken from Bisi *et al.* [32] and the values of the mean free paths, λ, have been taken from Rajopadhye *et al.* [33]. The amount of matter, x g/cm^2, which the primary beam has traversed can be seen in Table 6. The flux values at the top of the atmosphere are taken from Table 5.

Table 6. The distance (x g/cm^2) to the cosmic ray source.

Fragmentation probabilities at the extrapolation to the top of the atmosphere according to	x g/cm^2
Noon *et al.*	5
Rajopadhye *et al.*	10
Cester *et al.*	8

A mean value of the three figures in Table 6 gives 8 g/cm^2, which corresponds to about one mean free path for the L- and M-nuclei. Our statistics are poor, but the figures give some idea of the magnitude of the distance to the cosmic ray source.

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